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In search of massive single-population globular clusters

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ABSTRACT

The vast majority of globular clusters so far examined shows the chemical signatures of hosting (at least) two stellar populations. According to recent ideas, this feature requires a two-step process, in which the nuclearly processed matter from a 'first generation' (FG) of stars gives birth to a 'second generation' (SG), bearing the fingerprint of a fully carbon–nitrogen–oxygen (CNO) cycled matter. Since, as observed, the present population of most globular clusters is made up largely of SG stars, a substantial fraction of the FG ($\gtrsim$90 per cent) must be lost. Nevertheless, two types of clusters dominated by a simple stellar population (FG clusters) should exist: clusters initially too small to be able to retain a cooling flow and form a second generation (FG-only clusters) and massive clusters that could retain the CNO-processed ejecta and form an SG, but were unable to lose a significant fraction of their FG (mainly-FG clusters). Identification of mainly-FG clusters may provide an estimate of the fraction of the initial mass involved in the formation of the SG. We attempt a first classification of FG clusters, based on the morphology of their horizontal branches (HBs), as displayed in the published catalogues of photometric data for 106 clusters. We select, as FG candidates, the clusters in which the HB can be reproduced by the evolution of an almost unique mass. We find that less than 20 per cent of clusters with [Fe/H] < -0.8 appear to be FG, but only $\sim$10 per cent probably had a mass sufficient to form at all an SG. This small percentage confirms on a wider data base the spectroscopic result that the SG is a dominant constituent of today's clusters, suggesting that its formation is an ingredient necessary for the survival of globular clusters during their dynamical evolution in the Galactic tidal field. In more detail we show that Pal 3 turns out to be a good example of FG-only cluster. Instead, HB simulations and space distribution of its components indicate that M53 is a 'mainly-FG' cluster that evolved in dynamic isolation and developed a small SG in its core thanks to its large mass. Mainly-FG candidates may also be NGC 5634, NGC 5694 and NGC 6101. In contrast, NGC 2419 contains $>$30 per cent of SG stars, and its present dynamical status bears less information on its formation process than the analysis of the chemical abundances of its stars and of its HB morphology.

Key words: stars: abundances – stars: horizontal branch – globular clusters: general – globular clusters: individual: NGC 2419 – globular clusters: individual: M53 – globular clusters: individual: Pal 3.

1 INTRODUCTION

A general finding of recent years is that all globular clusters (GCs) so far spectroscopically examined contain multiple stellar populations. This is significatively shown in the recent analysis of Carretta et al. (2009) of about 2000 stars in 19 GCs, which shows that all these clusters display the sodium–oxygen (Na–O) anticorrelation, signature of the presence of a population of stars sodium richer and oxygen poorer than the halo stars of the same metallicity. The Na–O anticorrelation is typical of GCs, whose constituent stars belong to two or more stellar populations differing in the abundances of the elements produced by the hot carbon–nitrogen–oxygen (CNO) cycle and by other proton-capture reactions on light nuclei. In fact, these chemical signatures are present also in turn-off stars and among the subgiants (e.g. Gratton et al. 2001; Briley, Cohen & Stetson 2002; Briley et al. 2004), so they cannot be imputed to '*in situ*' mixing in the stars, but must be due to some process of self-enrichment occurring at the first stages of the cluster life. Pieces of photometric evidence for the presence of multiple populations are also numerous and sometimes suggestive of star formation occurring in separate

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successive bursts. The photometric signatures of different populations can be imputed in part to helium differences, inferred from the morphology of the horizontal branches (HBs; D'Antona et al. 2002; D'Antona & Caloi 2004; Lee et al. 2005), or from the presence of multiple main sequences (Norris 2004; Piotto et al. 2005, 2007).

In view of all this, at present the formation of globular clusters is considered a two-step process lasting no longer than ∼100 Myr, during which the nuclearly processed matter from a 'first generation' (FG) of stars gives birth, in the cluster innermost regions, to a 'second generation' (SG) of stars with the characteristic signature of a distribution of element abundances fully CNO cycled.

In this regard, a major problem remains and is rarely faced: the spectroscopic information shows that, in the clusters so far examined, the percentage of stars of the SG is generally ∼50–80 per cent (Carretta et al. 2009), as also show the results by interpreting the HB morphologies in terms of helium enrichment (D'Antona & Caloi 2008). This large percentage cannot be the result of chemical evolution within a 'closed box', simply because the processed matter available from the more massive stars is always a small percentage of the FG mass.[1] Anomalous initial mass functions (IMFs) of the FG may help to increase this percentage, but they pose further problems for the dynamical survival of clusters; instead, it seems necessary that the matter forming the SG stars is collected from a much larger stellar ensemble. In other words, the cluster has managed to lose most of its FG stars, and is now the 'small' remnant of the evolution of a much more massive – and maybe also of a much bigger – stellar system.

So the first proposal on the subject, by Bekki & Norris (2006), assumes that all GCs are formed within dwarf galaxies, which are now dispersed. This kind of formation is generally accepted to have occurred in the most massive clusters, such as in ω Cen M22, and in M54, the cluster that belongs to the Sagittarius dwarf galaxy (Ibata, Gilmore & Irwin 1994; Bellazzini et al. 2008). These clusters also show metallicity spreads (e.g. among others Norris & Da Costa 1995; Marino et al. 2009; Carretta et al. 2010a) that are not present in most of the other clusters. It is more difficult to believe that *all* GCs have formed within dwarf galaxies. We point out e.g. that old massive clusters in the Magellanic Clouds also show the Na–O anticorrelation (Mucciarelli et al. 2009).

A different proposal to explain the presence of multiple stellar populations in Galactic GCs, with the observed number fractions of FG and SG stars, was advanced by D'Ercole et al. (2008). The model is based on the loss of the most of the FG stars at early phases during the formation of the SG stars in a cooling flow at the cluster's centre. The idea in support of this model is that the mass-loss from the explosion of Type II supernovae (SNe II) and the associated loss of the remnant gas from which the FG stars had formed, occurring just previous to the formation of the SG, produce an expansion of the cluster, leading to a loss of a significant fraction of FG stars. D'Ercole et al. (2008) show that 90 per cent or more of the initial FG mass may be lost, so that the SG may become an important fraction of the total stellar population, even overcoming the FG. However, if the total size of the cluster was strongly under filling its tidal radius, or the cluster evolved in isolation, the FG cannot be lost and the cluster dynamically survives to the SN II epoch, maybe leaving a looser cluster structure as a fingerprint of the mass-loss from the SN II explosions (e.g. Bastian et al. 2008; Vesperini, McMillan & Portegies Zwart 2009). In this case, the SG formation remains *a small perturbation in the cluster history*, and cannot represent more than a few per cent of the total mainly-FG cluster.

Of course, true 'FG-only' clusters should exist: those in which an SG could not form because their initial mass was too low to allow for the formation of a cooling flow (D'Ercole et al. 2008; Vesperini et al. 2010; Bekki 2011). These clusters will generally survive only if they do not interact strongly with the Galactic gravitational field; otherwise, the expansion due to the SN II mass-loss will lead to the cluster disruption. The fact that most GCs so far examined host a large fraction of SG stars seems to imply that the very formation of an SG – that occurs after the SN II epoch and is not subject to the cluster expansion – and its dynamical interaction with the FG stars allowed massive clusters to survive in a tidally limited environment (D'Antona & Ventura 2008), although they lose more than 90 per cent of the initial mass.

A dynamical identification of these two important classes of clusters (FG-only and mainly-FG) is particularly complicated as it would require a reliable reconstruction of the individual cluster's dynamical histories and initial structural properties. For example, NGC 2419 strongly underfills its Jacobi radius ($r_{\rm J}$), the tidal radius of the cluster due to the galactic field, computed in the plain Roche approximation (e.g. Portegies Zwart, McMillan & Gieles 2010), defined by its present mass and Galactocentric distance; on the basis of its current structural properties and position in the Galaxy, one might naively consider NGC 2419 to be a good candidate of a 'mainly-FG' cluster. However, as discussed in Cohen et al. (2010) and Di Criscienzo et al. (2011b), its eccentric orbit (Casetti-Dinescu et al. 2009) and/or, possibly, a different galactic environment in its early stages of evolution must have caused a large mass-loss, and this cluster appears to contain a significant fraction of SG stars.

We point out that the formation of the SG subsystem is likely to have a significant impact on the cluster structural properties. While young clusters in nearby galaxies form compact, with a half-mass radius $r_{\rm h} < 1$ pc (Lada & Lada 2003), they expand thanks to mass-loss by stellar winds and SN II explosions in the first 30 Myr of life (e.g. Bastian et al. 2008), and this expansion may be enhanced if the cluster is initially mass segregated (Vesperini et al. 2009). If the SG forms in a cooling flow, this leads naturally again to an even more compact stellar distribution (D'Ercole et al. 2008), with a small $r_{\rm h}$.[2] Otherwise, if the SG does not form, the cluster maintains the larger $r_{\rm h}$ acquired in the first expansion phase, so a cluster may be tidally filling (e.g. $r_{\rm h}/r_{\rm J} > 0.1$; Baumgardt et al. 2010) simply because it has not developed an SG.

Considering the possible ambiguities in the identification of FG-only and mainly-FG clusters from dynamical information and from their present structure, we have decided to resort to a photometric criterion based on the evolutionary status of their HBs. In this work, we examine the existing astronomical literature to identify clusters that we expect to be either FG-only (low initial mass) or mainly-FG (high initial mass) clusters. If we can identify mainly-FG clusters, and discover the presence of a small percentage of SG stars in them,

[1] In the case of massive asymptotic giant branch (AGB) polluters, the mass consistent with the chemical anomalies (including both processed ejecta and diluting gas) goes from ∼8 to 12 per cent of the initial cluster mass, depending on the IMF, see e.g. Vesperini et al. (2010).

[2] As shown by Vesperini et al. (2011), a further indication that the SG is more centrally concentrated than the FG lies in the lack of barium stars in the SG of several clusters (D'Orazi et al. 2010).

this will help constraining the model for the formation of multiple generations in GCs.

2 SELECTION OF FG-ONLY CLUSTERS

One easy way to recognize the presence of a second generation in a GC is to consider the morphology of the HB (e.g. D'Antona et al. 2002; Gratton et al. 2010). Historically, the dispersion in mass along the HB was imputed to a dispersion in mass-loss (Rood 1973), but recent developments have shown that it may be in large part due to differences in the helium content that appears together with the chemical signatures of the second generation (Marino et al. 2011, and references therein). As discussed in D'Antona & Caloi (2008), bimodal HBs, blue tails, gaps in the stars distribution and, in general, HBs that extend from the red to the faint blue are the most clear candidates for the presence of multiple stellar generations. As for less extreme morphologies, the case of M3 was examined in detail by Caloi & D'Antona (2008). While an appropriate dispersion in mass-loss ($\sigma \sim 0.02$ $M_{\odot}$; Catelan, Ferraro & Rood 2001) allows us to reproduce the ratios in a number among the HB components (red, variable and blue), the detailed colour distribution along the HB and the RR Lyrae peaked period distribution cannot be reproduced by a 'normal' population with mass spread. In contrast, a generation of stars with normal helium, with a very small-mass dispersion ($\sigma \lesssim 0.003\,M_{\odot}$) can account very well for the red and variable HB members, while the blue region is populated by a second star generation with variable helium. The very good fit obtained in these conditions for the number versus period distribution of RR Lyrae stars, otherwise unattainable (Catelan 2004; Castellani, Castellani & Cassisi 2005) strongly supports this interpretation.

In this framework, the single-population GCs should be identified by an HB that can be reproduced by *the evolution of an almost unique mass*. We adopt the presence of a 'short' HB as a first indication of an FG cluster and then consider its dynamical status. To single out the candidates, we examined the colour–magnitude (CM) diagrams in the data bases by Rosenberg et al. (2000a), 2000b) and by Piotto et al. (2002), covering a total of 96 GCs. Besides, we took into account five other clusters (NGC 5686, NGC 6749, NGC 7492, Arp2 and Terzan 8) for a total of 101 CM diagrams present in the current literature. Clusters with bad CMs, insufficient for our purposes (e.g. CM diagrams of clusters in the bulge or projected on to it), have not been considered. Besides, we exclude those clusters with [Fe/H] > -0.8 that show an exclusively red HB. In these cases, even if an SG is present, it is not easily identifiable with simple photometric criteria (see e.g. the case of 47 Tuc discussed in Di Criscienzo et al. 2010).

After this first screening, we are left with 86 CM diagrams, among which FG clusters must be identified. Only one cluster is left with a red HB (NGC 6652). For the others, whose HB is blue, we select those in which the extension in V magnitude of the HB does not exceed 1 mag. We further exclude the clusters (with a short blue HB) for which the O–Na anticorrelation has been observed, namely: M30, NGC 6397 (Carretta et al. 2009) and NGC 7492 (Cohen & Melendez 2005). When available, we checked the results on more than one CM diagram. These checks allowed us to eliminate clusters that in a first moment looked like an FG. A clear example is given by NGC 6535, which looks like hosting a blue HB of about 1 visual magnitude range in the data by Testa et al. (2001). A look at the photometry by Sarajedini (1994) shows that the HB extends for $\sim$1.8 visual magnitudes, and, furthermore, that it contains two very faint extreme HB stars. On this basis, this cluster was excluded.

We consider, in addition, a group of small mass (1.5–4.5 $\times$ 10^4 $M_{\odot}$), far away clusters (galactocentric distance $d_{gc} \gtrsim 70$ Kpc): AM1, Eridanus, Pal 3, Pal 4, Pal 14, apparently 1–2 Gyr younger than M3, but of similar metallicity. Their HBs are short, exclusively red, except for Pal 3, in which seven RR Lyrae variables are found. They all appear as good candidates for FG-only clusters.

Out of the 86 clusters we selected 12 clusters as FG (14 per cent). To this figure we may add the five clusters listed above. This constitutes $\sim$19 per cent of the galactic GCs for which we have reasonably good CM diagrams. This estimate may be a lower limit (as we have excluded the red HB, metal-rich clusters), but a detailed exam of the sample may also show that it is an upper limit. Note in fact that three clusters with the same photometric characteristics have been excluded on the basis of spectroscopy, which is not yet available for the clusters in the list.

Data for the selected clusters are presented in Table 1, where we also list NGC 2419, to be discussed later. [Fe/H], absolute visual magnitude M_v and the distances from the Sun ($d_{\odot}$) and from the Galactic centre (d_{gc}) are taken from Harris (2003). The mass is computed by assuming a mass to visual luminosity ratio of 2. The half-mass radius is either directly taken from Baumgardt et al. (2010) or computed according to their prescription (assuming that the true half-mass radius is 1.33 times the projected half-mass radius given by Harris 2003). The Jacobi radius is computed according to Baumgardt et al. (2010) prescription. In Column 10, we list the number of known RR Lyrae stars, if any, and in Column 11 we indicate the predominant colour of the HB (generally B = blue, only one R = red cluster is present) and whether the star distribution appears peaked (p; like in M53) or more distributed (d). The presence of RR Lyrae is a further indication of the extension in colour of the HB, although the fact that they are generally very few indicates that the RR Lyrae's gap is likely traversed by stars evolving out of the zero-age horizontal branch (ZAHB; see later).

Several of the 17 selected clusters have a small (present) mass. It is possible that also in the past this mass was small enough that the clusters could not form the SG stars. Recent hydrodynamic 1D computations by Vesperini et al. (2010), covering a wide range of cluster structural parameters, show that all the ejecta that may form SG stars are retained above $\sim10^6\,M_{\odot}$ of *initial* cluster mass, while the retention is very limited for all models of initial mass $\lesssim10^5$ $M_{\odot}$. Taking into account that clusters in Table 1 may have lost mass, due to two-body relaxation processes and tidal shocks, we may adopt a conservative limit of log ($M_c/M_{\odot}$) < 4.8 as a formal dividing line below which clusters do not form SG stars (FG-only). This choice selects eight clusters in Table 1, seven of which are also in the list of tidally filling clusters at $d_{gc} > 8$ kpc by Baumgardt et al. (2010). The other clusters in common between ours and those of the Baumgardt et al. (2010) list are the compact clusters ($r_h/r_J < 0.05$) M53, NGC 5694 and NGC 5634. We suggest then that the small-mass clusters have a larger r_h because *they did not form the SG*, as outlined in Section 1.

In our list, we are left with nine clusters ($\sim$10 per cent) that may have initially developed an SG. This small fraction is consistent with, and extends, the spectroscopic result by Carretta et al. (2009), 2010b), who find in their whole 19 clusters sample a predominant ($>$50 per cent) SG. We must conclude that very few of the clusters that may develop the SG do not lose a high fraction of their initial mass or even that only a few clusters that do not form an SG *survive* to the dynamical interaction with the Galactic tidal field. The formation of a central compact SG system appears to

Table 1. Candidates FG clusters, plus NGC 2419.

Name	[Fe/H]	$M_{\rm v}$	log $M_{\rm c}$	$d_{\odot}$(kpc)	$d_{\rm gc}$ (kpc)	$r_{\rm c}$ (pc)	$r_{\rm h}$(pc)	$r_{\rm J}$	RR Lyrae	HB
NGC 4372	−2.09	−7.79	5.34	5.8	7.1	3.92	8.75	78.8	0 (A)	B, d (a)
NGC 5024 (M53)	−1.99	−8.70	5.71	17.8	18.3	2.48	7.66	197.0	59 (n)	B, p (n)
NGC 5634	−1.88	−7.69	5.31	25.2	21.2	2.05	5.27	160.0	20 (B)	B, p (b)
NGC 5694	−1.86	−7.81	5.36	34.7	29.1	0.80	4.43	205.5	0 (A)	B, p (c)
NGC 5897	−1.80	−7.21	5.12	12.4	7.3	9.40	10.12	67.8	11 (C)	B, p? (d,e,f)
NGC 6101	−1.82	−6.91	5.00	15.3	11.1	6.81	10.12	81.7	0 (A)	B, p (g)
NGC 6139	−1.68	−8.36	5.58	10.1	3.6	0.54	3.20	60.2	4 (A)	B, d (c)
NGC 6235	−1.40	−6.44	4.82	11.4	4.1	1.59	3.70	36.8	3 (A)	B, d (c,h)
NGC 6652	−0.96	−6.66	4.91	10.1	2.7	0.28	2.54	29.7	0 (A)	R (c)
NGC 6717	−1.29	−5.66	4.50	7.1	2.4	0.22	1.86	20.1	1 (A)	B, d (a,c)
Arp 2	−1.76	−5.29	4.35	28.6	21.4	17.60	21.13	76.9	9 (B)	B, d (i)
Terzan 8	−2.00	−5.05	4.26	26.0	19.1	10.06	10.06	66.7	3 (B)	B, p? (j)
AM1	−1.80	−4.71	4.12	121.9	123.2	7.09	23.64	207.0	0 (A)	R (k)
Eridanus	−1.46	−5.14	4.29	90.2	95.2	8.74	14.00	198.6	0 (A)	R (l)
Palomar 3	−1.66	−5.70	4.51	92.7	95.9	17.25	23.7	236.4	7 (j)	R (j)
Pal 4	−1.48	−6.02	4.64	109.2	111.8	23.29	22.87	289.2	0 (A)	R (l)
Pal 14	−1.52	−4.73	4.13	73.9	69.0	26.94	32.96	141.7	0 (A)	R (k)
NGC 2419	−2.12	−9.58	6.06	84.2	91.5	11.40	23.78	753.0	75 (D)	B, p+bh (m)

References: (a) Brocato et al. (1996); (b) Bellazzini, Ferraro & Ibata (2002); (c) Piotto et al. (2002); (d) Ferraro, Fusi Pecci & Buonanno (1992); (e) Sarajedini (1992); (f) Testa et al. (2001); (g) Marconi et al. (2001); (h) Howland et al. (2003); (i) Buonanno et al. (1995); (j) Montegriffo et al. (1998); (k) Hilker (2006); (l) Stetson et al. (1999); (m) Di Criscienzo et al. (2011b); (n) Rey et al. (1998); (A) Clement et al. (2001); (B) Salinas et al. (2005); (C) Clement & Rowe (2001); (D) Di Criscienzo et al. (2011a).

be a key ingredient for the survival of a cluster to the first phases of cluster evolution (D'Antona & Ventura 2008; D'Ercole et al. 2008).

3 THE CASES OF PALOMAR 3 AND M53

We examine in detail two clusters: Pal 3 (an example of FG-only cluster) and M53 (for which we pose the case of a mainly-FG cluster). For comparison, we also discuss the case of NGC 2419: although it is now evolving fully inside its Jacobi radius, the cluster contains a substantial extreme SG, implying a peculiar dynamical history. The HBs of these three clusters are shown in Fig. 1, together with the histograms of the colour and magnitude distribution of HB stars. It is straightforward to appreciate that Pal 3 HB is extremely short and that the HB of M53 shows a very peaked distribution in colour, with a tail of redder stars. The strikingly different HB of NGC 2419 not only shows a strongly peaked colour and magnitude distributions for its more luminous HB component, as in M53, but has also a long tail of bluer stars, ending with a blue hook.

3.1 Simulations

The HB simulations for Pal 3 and M53 are based on the models published in D'Antona et al. (2002) for metallicity $Z = 2 \times 10^{-4}$ and 10^{-3}, with solar-scaled α-element abundances. Helium contents of $Y = 0.24$ and 0.28 are considered. The simulations for NGC 2419 are based on the models presented in Di Criscienzo et al. (2011b) for a mixture with [Fe/H] = −2.4 and [α/Fe] = 0.2. Helium contents of $Y = 0.24$, 0.28 and 0.42 have been considered. A detailed description of models is given in the quoted papers.

Synthetic models for the HB are computed according to the recipes described in D'Antona & Caloi (2008). We adopt the appropriate relation between the mass of the evolving giant $M_{\rm RG}$ and the age, as a function of the helium content and metallicity. The mass

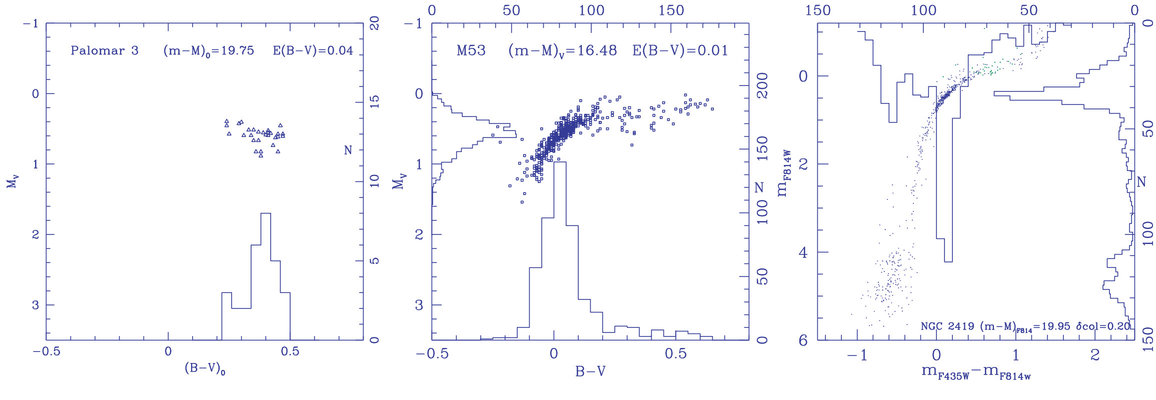

Figure 1. HB stellar distributions for three very different cases. Left-hand panel: Pal 3 from Hilker (2006); central panel: M53 data from Rey et al. (1998); right-hand panel: NGC 2419 from Di Criscienzo et al. (2011b). The histograms represent the number counts of HB stars as a function of the colour (all panels) and magnitude (central and right-hand panel).

of the HB is then

$$M_{\rm HB} = M_{\rm RG}(Y, Z) - \Delta M. \quad (1)$$

Here, ΔM is the mass lost during the RG phase. We assume that ΔM has a Gaussian dispersion σ around an average value ΔM_0 and that both ΔM_0 and σ are parameters to be determined and *in principle* do not depend on Y. Once Z and Y chosen, the $T_{\rm eff}$ location of an HB mass is fixed. Consequently, different ages can be adopted, provided that the mass-loss is consistently adjusted. For HBs extending into the variability region, the RR Lyrae are identified as those stars that, in the simulation, belong to the $T_{\rm eff}$ interval, $3.795 < \log T_{\rm eff} < 3.86$. Their periods are computed according to the pulsation equation (1) by Di Criscienzo, Marconi & Caputo (2004).

3.2 Palomar 3

Palomar 3 is a remote cluster at about 96 kpc from the Galactic centre and an estimated orbital minimum distance from it is ∼82.5 kpc (Dinescu, Girard & van Altena 1999). Since its proper motion is uncertain, it is considered possible that it may not be bound to the Galaxy and that it may be falling on to it for the first time. Pal 3 is one of the most extended clusters with a half-light radius of about 24 pc and a truncation radius of about 130 pc. It is faint, with $M_{\rm v} \sim -5.7$, and its destruction time is estimated to be about 20 Hubble times (Gnedin & Ostriker 1997).

Two CM diagrams of Pal 3 are available (Stetson et al. 1999; Hilker 2006). This tiny cluster presents a sparse but well-defined red giant branch (RGB) and an HB populated in the red and variable regions; the turn-off luminosity suggests an age slightly lower than that of M3, by ∼1 Gyr (VandenBerg 2000; Catelan et al. 2001) or ∼2 Gyr (Stetson et al. 1999) – see also Hilker (2006). Catelan et al. (2001) investigated the CM diagram in the context of the 'second-parameter' problem, in comparison with that of M3. By means of HB simulations, they found that a mass dispersion of $\sigma \sim 0.02\,{\rm M}_\odot$ was required to reproduce the HB of M3, while the HB of Pal 3 was consistent with a null mass dispersion. The chemical composition has been investigated by Koch, Côté & McWilliam (2009); they obtained high-resolution spectra for four red giants and determined the abundances for 25 elements (α-, iron-peaked, neutron-capture elements). The sample is limited, but a few results appear relatively safe: the α-enhancement is compatible with that found in halo field stars and typical GCs as M13; so are the Fe-peaked and neutron-capture element ratios. In addition, Koch et al. (2010) find that the n-capture elements appear to derive from the r-process only, as observed only in the very metal poor field stars (Honda et al. 2007) and in the GC M15 (Sneden, Pilachowski & Kraft 2000). Then, the n-capture patterns in Pal 3 do not require enrichment processes other than occurring in SN II explosions. Besides, an Na–O anticorrelation is not evident, although a weak one cannot be ruled out by Koch et al.'s data.

On the basis of the chemical and structural characteristics of the cluster, that is, the absence of s-process elements and anticorrelations (admittedly, an absence not yet safely established) we may consider Pal 3 as a good candidate to an FG-only cluster. For what concerns the dynamical evolution, let us note however that Sohn et al. (2003) found a weak evidence of tidal extensions around the cluster, out to ∼4 times the tidal (truncation) radius. In view of the long relaxation times at the centre and at $r_{\rm h}$ (7×10^9 and 8×10^9 yr, respectively) and the estimated extremely long destruction time, we think that, in any case, such extra-tidal objects should constitute a minor side effect.

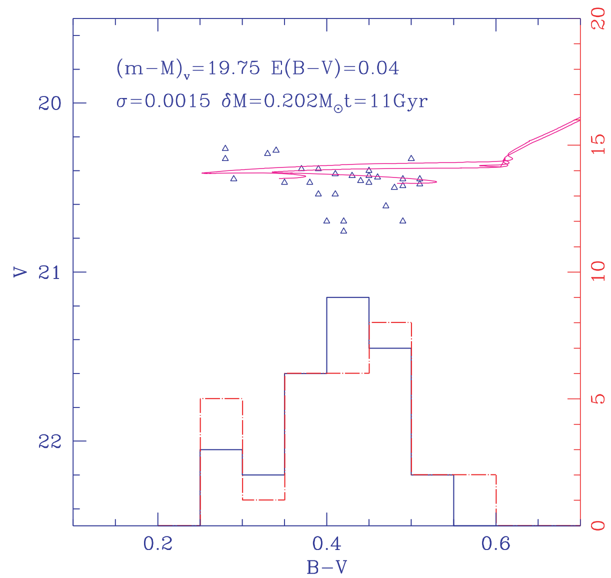

Figure 2. HB stellar distribution as observed by Hilker (2006), and superimposed simulation.

In Fig. 2, we show the result of a simulation of the HB distribution. The HB stars are taken from Hilker (2006). We find, as expected, a very small-mass spread, $\sigma = 0.0015\ {\rm M}_\odot$, consistent with previous estimates (Catelan et al. 2001). Therefore, the 'HB criterion' corresponds well to the other properties of this cluster, that is, confirmed to be an FG-only cluster.

3.3 M53 (NGC 5024)

This cluster is rather massive, with $M_{\rm v} = n - 8.70$ and $M = 5 \times 10^5\ {\rm M}_\odot$. The relaxation times at the centre and at $r_{\rm h}$ are 5.8×10^8 and 4.6×10^9, respectively. Its destruction time is given by Gnedin & Ostriker (1997) as about 30 Hubble times. It is rather far away at 18.3 kpc from the Galactic centre at a height above the Galactic plane of 17.5 kpc. It is generally considered among the very metal poor clusters ([Fe/H] = −1.99; Harris 2003). The present $r_{\rm h}/r_{\rm J}$ is 0.039, and its maximum value at the perigalactic distance of 15.5 kpc (Allen, Moreno & Pichardo 2006) is only slightly larger (0.044). Therefore, this cluster appears to have evolved always well inside its gravitational well.

The first indication that M53 may be an FG cluster[3] comes from the CM diagram. Its short HB barely reaches $B - V = -0.05$, with very few stars beyond this colour. In the cluster there are 59 known RR Lyrae variables of Oo type II (Kopacki 2000); a complete sample of the HB gives 12 red HBs, 35 variables and 257 blue HBs, these last ones almost all concentrated in a clump at a colour close to the blue edge of the variable region (Rey et al. 1998). At the metallicity of M53, the HB tracks beginning in the colour region of this clump ($B - V \sim 0.0$) evolve directly towards the red (Sweigart & Gross 1976; Di Criscienzo et al. 2011b, see also the left-hand

[3] D'Antona & Caloi (2008) examined the HB structure of this cluster and considered that it could be one of those GCs in which the FG had been completely lost, together with NGC 6397 and M13. For M53 the main feature leading to this conjecture was the possible presence of a high nitrogen content in the integrated spectrum (Li & Burstein 2003). Here we have more information that make us prefer the first stellar generation as the only one present, and not the second.

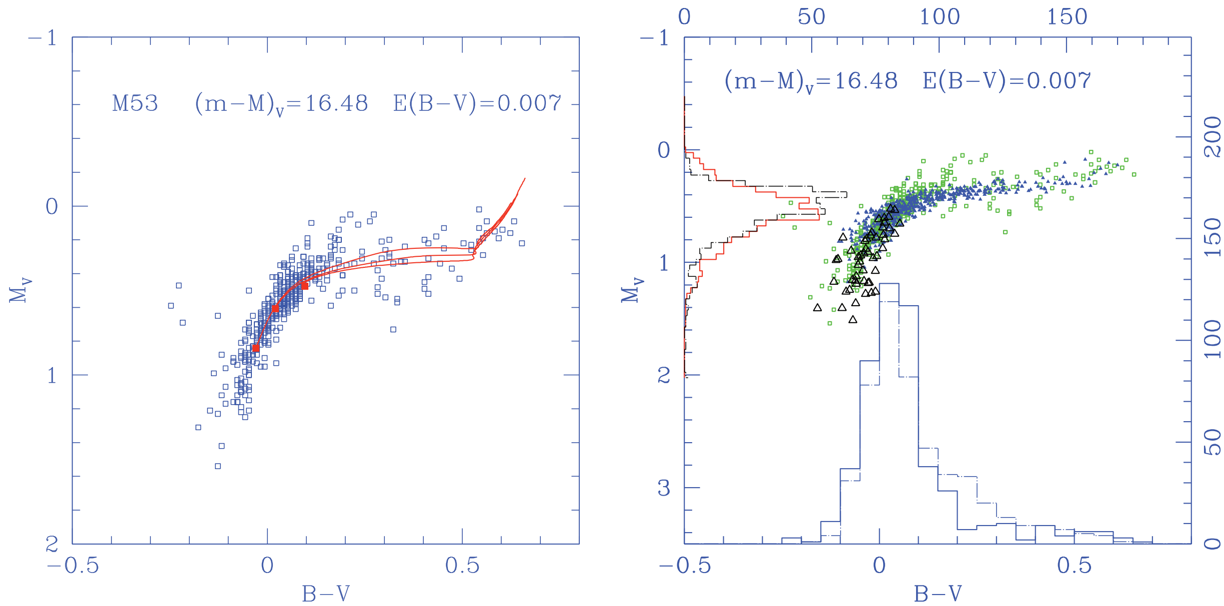

Figure 3. Left-hand panel: we show the HB tracks of $M = 0.68$, 0.70 and 0.72 $M_{\odot}$ for $Y = 0.24$, $Z = 0.0002$ superimposed on the data by Rey et al. (1998). Right-hand panel: a successful simulation (triangles) is superimposed on the data by Rey et al. The blue-filled triangles correspond to stars with $Y = 0.24$, while the black open triangles are the stars with $Y = 0.26$ and 0.27 (see the text). The full histograms on the sides represent the number versus magnitude and number versus colour distributions, as observed (full lines) and simulated (dot-dashed lines).

panel of Fig. 3), and an HB of this type is the result of the evolution of a well-defined HB mass, with a very small dispersion in mass-loss. The RR Lyrae and the red HB are the tails of the evolution of this typical evolving HB mass. This hypothesis is confirmed by the simulations described in the following. A very similar situation is found in the upper HB of NGC 2419, and is examined in extensive detail in Di Criscienzo et al. (2011b).

The presence of chemical inhomogeneities has been investigated by Martell, Smith & Briley (2008), who studied the absorption bands of CN and CH. What they found is 'a broad but not strongly bimodal distribution of CN bandstrength'. In their fig. 6 they compare it with the situation in NGC 6752: while in the latter cluster the CN distribution is neatly bimodal, in M53 it appears as a single Gaussian with a 'hunch' on the shoulder towards higher abundances (see their fig. 3, but see also Smolinski et al. 2011). Unfortunately, we cannot infer information on the existence of an anticorrelation C–N from these data, since metal-poor clusters do not show the CH–CN anticorrelation, even in the presence of the C–N bimodality (see the results for M15 by Cohen, Briley & Stetson 2005). Nevertheless, on the basis of the relatively small range in C and N abundance variation in M53, Martell et al. observe that may be 'the polluting material was not processed through the full CNO cycle', in which case the cluster should not show the Na–O anticorrelation.

In order to better define at what level M53 is dominated by the FG, we performed simulations of the HB morphology of this cluster. As the HB population is strongly peaked at $V \sim 17.0$ mag and $B - V \sim 0.0$, and the HB evolution is strictly redward, there is no possibility of reproducing the sparse blueward extension unless we hypothesize that (1) either the mass-loss on the RGB is slightly asymmetric or (2) the bluest HB members have a slightly larger helium content, so that they have a smaller progenitor mass. In this latter case, a small SG population would be present, characterized by this small increase in helium.

Our simulations are performed according to this second framework. We assumed $V = 17.4$ mag as the luminosity separating the main body of the HB from a short tail of stars with a possibly different origin. We considered a total of 450 HB stars with $V < 17.4$ mag, plus 50 fainter stars with $V > 17.4$ (see below). This number has been obtained by scaling the data by Rey et al. (1998) with respect to the total number of RR Lyrae variables with known periods (59). As for the RR Lyrae, we tried to reproduce their period distribution.

It was possible to reproduce the entire HB at $V < 17.4$ attributing to the cluster an age of 12 Gyr, a standard helium content $Y = 0.24$ and an average mass-loss on the RGB of 0.113 $M_{\odot}$, with a dispersion $\sigma(M) = 0.015$ $M_{\odot}$; a Gaussian error of 0.03 mag has been associated with both B and V magnitudes. Other choices of parameters can be made with equivalent success, e.g., a smaller mass dispersion can be associated with larger observational errors. For the fainter HB, we assume a slightly higher Y content, from 0.26 to 0.27. A successful simulation, superimposed to Rey et al.'s data, with the mentioned choices for the distance modulus and the reddening, is shown in the right-hand panel of Fig. 3.

The average evolving mass on the HB is 0.7 $M_{\odot}$. The simulated mass distribution as a function of the colour is shown in Fig. 4, where we see that the variable and red HB stars represent the tail of the distribution and can easily be interpreted as evolving from the ZAHB at 0.69–0.72 $M_{\odot}$. The ZAHB of the models with $Z = 0.0002$ and $Y = 0.24$ is also shown on the simulation. We can appreciate that very few ZAHB stars, with masses up to 0.74 $M_{\odot}$, are present at colours $B - V \sim 0.2$, as discussed above. As the RR Lyrae distribution with colour is dominated by stars already evolved from the ZAHB, it is statistically less constrained than the peak region. The total number and overall behaviour of RR Lyrae (see Fig. 5) are reasonably reproduced by the simulation presented in Fig. 4. We did not consider it necessary to obtain a better agreement of the period distribution, even if in principle this appears possible, as we know by experience (D'Antona & Caloi 2008). In our simulation, the slight asymmetry in the histogram of the number versus mass as shown in Fig. 4 is due to the presence of the small percentage of stars with a higher helium content, but the same result could be

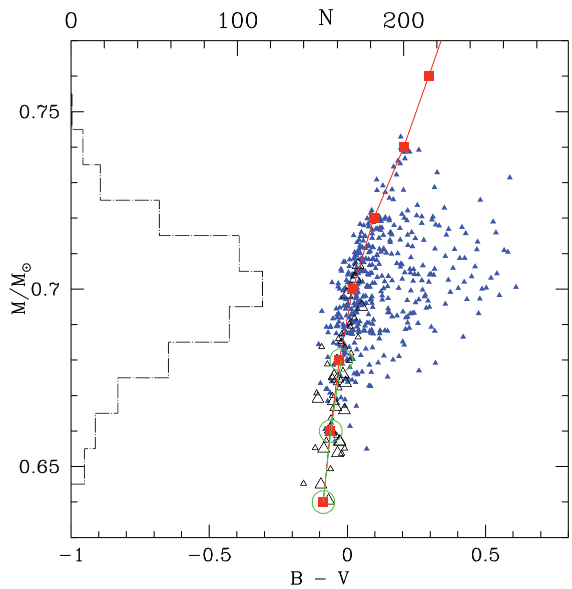

Figure 4. HB mass distribution as a function of colour for the simulation of Fig. 3. The blue-filled triangles have $Y = 0.24$, while the black smaller open triangles are the stars with $Y = 0.26$ and the larger open triangles have $Y = 0.27$. The histogram of the number versus stellar mass shown in the left-hand panel is the sum of the Gaussian distribution of the 450 stars with $Y = 0.24$ plus the slightly asymmetric extension towards smaller masses of the higher helium stars. The dots mark the ZAHB of the models adopted for the simulation, having chemistry Z = 0.0002 and $Y = 0.24$, while the three open circles show the (coincident) ZAHB of the models with $Y = 0.28$ that have been used to simulate the helium-increased population. Note that no difference appears in the colours versus mass, but the $Y = 0.28$ models are more luminous.

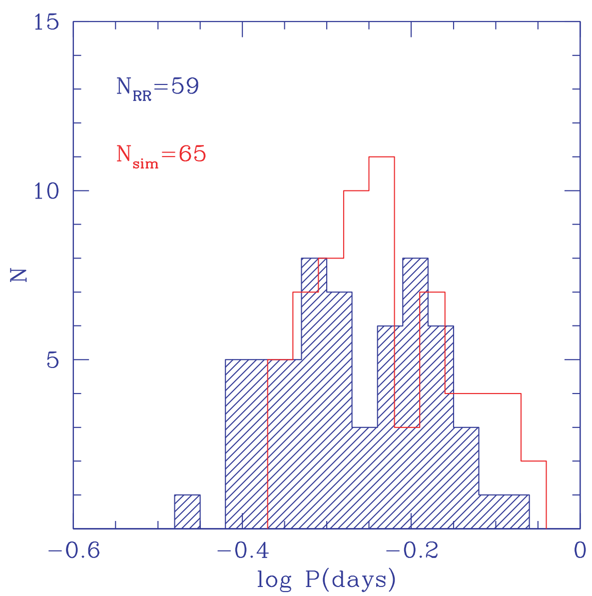

Figure 5. RR Lyrae distribution (shaded) from Kopacki (2000) and Clement et al. (2001), and a simulated distribution of periods from the simulation of Fig. 3.

obtained by assuming a slight asymmetry in the mass lost along the RGB.

We examined the relative spatial distribution of the faintest HB stars relative to the other HB members and to the red giants having

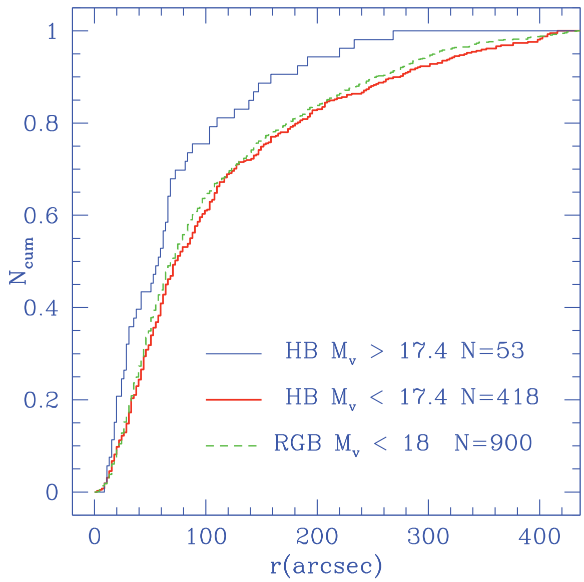

Figure 6. Cumulative distribution of the majority of HB stars (thick red line) is compared with the distributions of the bluest HB stars (upper blue line) and of the red giants (dashed green line). The sample has been divided by considering as 'extreme' all the HB stars at $M_v > 17.4$ mag.

$V < 18$. The comparison employs the Rey et al. (1998) data, converting the pixel scale of their data base by knowing that 1 pixel = 0.22 arcsec and is shown in Fig. 6. While the RGB and the main body of HB stars have the same cumulative distribution, the fainter HB stars appear indeed more concentrated. Is this an indication in favour of our interpretation, as the small SG would have formed in the very core of the cluster where the cooling flow concentrates the gas from the AGB ejecta? The study of dynamical mixing of two stellar generations, the second one formed exclusively in the core, is limited, until today, to the *N*-body simulations presented by D'Ercole et al. (2008) in the context of their model for GC formation. Further study is certainly needed to understand whether the current properties of M53 (Table 1) are consistent with the observed only partial mixing of SG and FG. M53 is not unique in this respect. For example, a central concentration for the SG is found in NGC 3201 by Kravtsov et al. (2010) and Carretta et al. (2010b), and in NGC 6752 by Kravtsov et al. (2010). The second line of interpretation, that the giants in the cluster core suffer stronger dynamical interactions and are subject to a stronger mass-loss, should also be carefully tested by modelling the interactions in the cluster core. At present, we suggest that spectroscopic information (e.g. the presence or lack of high sodium and low oxygen in a small fraction of M53 red giants) would be the best observational test of either hypothesis. At the present stage, we propose that the current data show some evidence that M53 is a 'mainly-FG' cluster.

Visual inspection of their CM diagrams indicates that NGC 5634, NGC 5694 and NGC 6101 have HB characteristics very similar to those of M53, so they can also be mainly-FG candidates, and it would be important to assess their chemical properties as well. Note that only NGC 6101 is tidally filling: the other three clusters (including M53) have a small ratio r_h/r_j, and actually lie close to the line giving the position of a cluster of 10^5 M$_\odot$ with r_h = 3 pc in the plane r_h/r_J *versus.* d_{gc} of fig. 2 in Baumgardt et al. (2010).

4 NGC 2419 VERSUS PAL 3 AND M53

Our analysis started from the consideration that the dynamical status of a cluster (tidally limited or not) at its formation time or later on during the course of its life would determine its evolution and survival. However, since it is not straightforward to go back from the present dynamical status to the previous dynamical evolution, we resorted to a pure photometric parameter (the morphology of the HB) to select FG clusters. In this way we have not only recovered that Pal 3 is an FG-only cluster (Koch et al. 2009, 2010), but have also shown that M53 may be an example of a mainly-FG cluster.

At this point it is relevant to enquire how a cluster would appear, in principle similar to M53, in which the SG appears to be a relevant constituent. We consider NGC 2419, a metal-poor, far away, isolated cluster (Table 1). It is twice as massive as M53, and much farther from filling its Galactic tidal radius than M53: the comparison between the truncation radius and Jacobi radius provides a ratio $r_t/r_J = 0.57$ for M53 and only 0.28 for NGC 2419. Given the similarity in heavy element abundance, we can compare the HBs of M53 and NGC 2419 (Fig. 1). As mentioned before, the brighter regions of the HB are very similar: the same concentration of HB members in a very small colour interval on the blue side of the variable region, with RR Lyrae and red HB stars likely the product of these blue stars, as discussed in the simulation of M53 HB (Fig. 3). But the HB in NGC 2419 continues, with a lower star density, well beyond the limit in M53, ending with the most populated ($\sim$30 per cent of the HB stars!) blue hook known in Galactic GCs (Ripepi et al. 2007). Although Sandquist & Hess (2008) argue that the symmetric distribution of stars along the MS favours a single stellar population model for this cluster, Di Criscienzo et al. (2011b) have discussed that both the HB morphology and the colour distribution of the giants suggest the presence of two well-separated populations, one of which has a very high helium content. They also show that the partial asymmetry that would result in the MS colour distribution would be hidden by the present photometric errors. If this is the case, the dynamical evolution of this cluster cannot have occurred in isolation, as a much larger initial mass would have been required to provide the 30 per cent very helium rich population presently found in NGC 2419. The small spread in calcium present among the giants in NGC 2419 (Cohen et al. 2010) also shows that this cluster was able to retain at least some SN II ejecta, spectroscopically excluding the FG-only possibility. In Fig. 7, we show a simulation of the whole HB of NGC 2419, well reproducing the whole extension in colour and magnitude of this extreme HB. In order to reproduce the upper HB we assumed $Y = 0.24$ and $\sigma = 0.008$ M$_\odot$. The long tail, between the more luminous peak of stars and the blue hook, is reproduced by 90 stars, and assuming the same helium content and a broader and larger mass-loss ($\Delta M = 0.22$ and $\sigma = 0.05$ M$_\odot$). A similar fit is obtained by assuming stars with an increased and variable helium content, and a smaller spread in mass-loss, as described above for M53. For the blue hook we assume $Y = 0.42$ and $\sigma = 0.01$ M$_\odot$. The blue hook simulation follows the prescriptions explained in Di Criscienzo et al. (2011b) to which we refer for details.

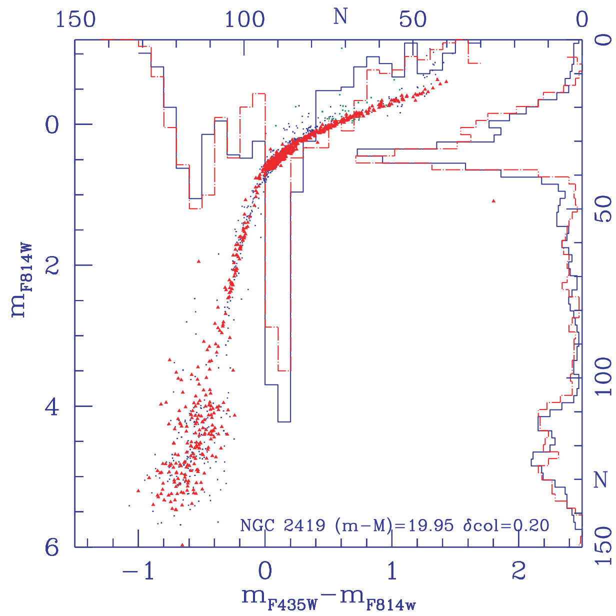

Figure 7. We show the HB data for NGC 2419 in the *Hubble Space Telescope* near-infrared magnitude m_{F814W} versus the colour $m_{F435W} - m_{F814W}$ presented in Di Criscienzo et al. (2011b). The histograms of colour and magnitude distributions are also shown as full (blue). Superimposed we show a simulation of the entire HB, obtained by fitting the luminous part with 390 stars having standard helium abundance $Y = 0.24$, mass-loss $\Delta M = 0.073$ M$_\odot$ and spread in the HB masses $\sigma = 0.008$, the middle part with 90 stars having the same $Y = 0.24$ and $\Delta M = 0.22$ M$_\odot$, $\sigma = 0.05$ M$_\odot$; the blue hook is reproduced with 160 stars with $Y = 0.42$, $\Delta M = 0.110$ M$_\odot$ and $\sigma = 0.01$ M$_\odot$. Further assumption of the models for the blue hook stars is provided in Di Criscienzo et al. (2011b). The histograms of the simulation are dot-dashed.

5 DISCUSSION

We adopted a simple photometric criterion (the extension of the HB) to select candidates for FG clusters from existing large data bases of CM diagrams of GCs. The list of 17 candidates is tentatively divided into eight FG-only clusters (that could not form an SG at all) and nine mainly-FG clusters (that could form an SG, but did not lose most of the FG mass). The small percentage of mainly-FG clusters indicates that very few of the clusters that develop the SG do not lose a high fraction of their initial mass, and we suggest that non-isolated clusters are destroyed by the dynamical interaction with the Galactic tidal field, unless they are able to form an SG, whose dynamical mixing with the FG stars allows the cluster to survive (see also D'Antona & Ventura 2008).

We studied in more detail the HBs of Pal 3, M53 and, for comparison, NGC 2419. We found a similarity between the HB in M53 and the upper HB in NGC 2419, the total cluster mass being the only evident difference between them. Given their structural similarity, we may be witnessing the influence of the total mass *only* on the first evolutionary stages in GC life (or at least in the very metal poor ones). The three clusters represent very different evolutionary cases as follows.

(1) Pal 3 is consistent with hosting an FG-only population.

(2) M53, a much more massive cluster, has an HB consistent with an almost pure FG population; by examining synthetic models for its HB stellar distribution, we suggest that a small second generation may be present (mainly-FG cluster), given by the bluest and faintest HB stars, mostly concentrated in the cluster inner regions.

(3) NGC 2419, more than double the mass of M53 and close in mass to the most massive clusters in the Galaxy, with an apparently 'evident' chemical and dynamical isolated evolution, exhibits a consistent blue hook, a crucial signature of the presence of multiple star generations. So it is reasonable to expect strong chemical anomalies in this cluster (O–Na and Mg–Al anticorrelations) – not yet observed, given its extreme distance. The presence of a small spread in calcium (Cohen et al. 2010) testifies however that this

cluster was able to retain at least some SN II ejecta, spectroscopically excluding the FG-only possibility.

We have presented reasons to support the hypothesis that M53 is a mainly-FG cluster. Were this the case, and if, as likely, the chemical and dynamical evolution of the cluster had taken place within its tidal radius, the interesting possibility would arise of estimating the percentage of second generation stars resulting from such evolution, after estimating the stellar losses due to two-body interactions during the Galactic lifetime. To clarify this scenario, it would be important to obtain a CM diagram of M53 with modern telescopes in order to establish with higher precision the colour of the population peak on the HB. In fact, the large part of the HB members with smaller colours can be assumed to belong to the second generation, once excluded the possibility of an asymmetry in mass-loss along the RG branch. This derives from the fact that the evolution of ZAHB members bluer than the RR Lyrae strip develops strictly redward. At present, the fraction of the SG seems to be $\sim$0.1 (=50/500), but this is surely an approximate value.

The consistency of HB morphologies with chemical characteristics known at present, even if encouraging, must be substantiated by spectroscopic investigations of the giant branches of all the three clusters, to put in evidence the presence/absence of, e.g., the Na–O anticorrelation. We hope that this information will help to establish a few firm points in this complex subject.

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